A RAND NOTE

Advanced Composite Materials: The Air Force's Role in Technology Development

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Prepared for the
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PREFACE

This RAND Note documents a study on the important institutional activities and processes that contributed to the timely maturation of advanced composite materials technology for use in combat aircraft structures. The primary purpose of this Note is to identify the roles that the Air Force (and other governmental organizations) played in the transition of composites from an emerging and potentially important military technology to the point of initial applications in new aircraft designs. This study was motivated by the hypothesis that the successful development of divergent technologies (for military purposes) may have some important and common institutional factors that can be identified. For example, the phasing of critical-technologies identification studies, the enduring presence of technology advocates within the Department of Defense, and the funding of advanced technology development programs may all be as important to a maturation process as are those elements that are strictly technical in nature.

This work was performed in the Resource Management and System Acquisition Program within Project AIR FORCE. This Note supplements RAND report R-4199-AF, *Maintaining Future Military Aircraft Design Capability* (1992), which examines the general question of how to maintain combat aircraft design capabilities in rapidly changing threat and budget environments.

SUMMARY

Much of the defense industry in the United States may well experience significant contractions and structural changes as the defense budget continues to decline rapidly from its peak in the mid-1980s. Within some circles of the Department of Defense (DoD), this budgetary trend has raised concerns about both the health of many industries that support defense needs and their ability to develop state-of-the-art systems in the future. For example, will the seemingly inevitable contraction of the combat aircraft industry lead to a deficiency in this nation's ability to design and produce the next generation of advanced fighter, bomber, and attack aircraft?

This Note (which supplements RAND report R-4199-AF, *Maintaining Future Military Aircraft Design Capability,* 1992) addresses only one important aspect of the larger question of maintaining combat aircraft design skills: the timely maturation of new and militarily significant technologies. The focus on aircraft-related technologies seems justified for several reasons:

- These aircraft play a major role in the U.S. defense posture;
- The military value of these systems depends strongly on cutting-edge technologies;
- The lead time to develop and produce such aircraft, including the development of the advanced technologies necessary for each new generation, is measured in decades;
- There is only one U.S. buyer (DoD) for many of these systems.

The objective of this case study was to better understand how new aircraft technologies are matured and then assimilated by design teams. Although this objective can be succinctly stated, the answers are complex and they, in turn, raise many questions of their own. In particular, we seek to gain some insight about the roles that the Air Force and other governmental agencies play in forecasting, initiating, guiding, and funding technologies that are perceived to be of future military importance.

The information presented in this study is based upon both interviews and relevant reports. Wherever possible, interviews were conducted with individuals who observed and participated in the early development of advanced composites. Emphasis was placed on the interviews since the documentation that was gathered focuses more on technical issues and rarely discusses the more "process-oriented" questions posed by this study. It should be

noted that many government records concerning early research and development (R&D) on advanced materials were destroyed. These records, dating back to the 1940s, had been kept at the Materials Laboratory (Wright-Patterson Air Force Base), but regulations concerning the disposition of older documents resulted in their destruction since storage space at a historical office or agency was not available.

With respect to the role of the military in technology development, this study finds that:

- The Air Force organization played a key role in the identification, development, and early applications of advanced composites to combat aircraft.

In the late 1950s, the Air Force assumed a significant amount of the responsibility for the development of advanced materials. High-level advisory groups encouraged this attitude since the Air Force was perceived to have the greatest needs for high-performance materials given the increasing importance of supersonic flight, missile technology, and space flight. Air Force-sponsored research in the late 1950s helped to identify boron fibers (a component of the first "advanced" composite) as a promising new material for use in combat airframes. Technical feasibility of advanced composite structures was then established through flight-article demonstration programs that began in the mid-1960s. The research of the 1960s and early 1970s generated the initial, nonproprietary, technical databases that the airframe industry drew upon in order to become more familiar with advanced composites.

The Air Force, over a sustained period of time, acted as a technology advocate and used its funding to develop an initial production capability within the airframe industry. This funding was then used to motivate that industry to invest in the relatively costly design and manufacturing elements of advanced composites technology.

With respect to the length of the technology-development process and the level of commitment sustained by the Air Force, this study finds:

- Technology development can be a long-term commitment that is measured in decades and may last well beyond the point of initial application in a weapon-system design.

A new technology (e.g., composites) may be particularly susceptible to sluggish development if it is a radical departure from the existing standard (e.g., metals). In such cases, industry may be slow to adopt the technology since such adoption requires significant

new facilitation and retraining of existing personnel, as well as fundamental changes to the design, analysis, and manufacturing processes. If such a technology survives an initial development/feasibility phase, even more time will be required for the educational system to produce significant numbers of new scientists and engineers who think in terms of the new technology; this assumes, of course, that the academic community has been exposed to the new technology and is interested enough to expose it to students. Thus, long-term growth of critical technologies is in part dependent upon the degree to which the technologies become active research interests of the academic communities.

Another important part of the context to keep in mind is that the modern era of advanced composites technology was preceded by about twenty years of R&D and flight experience with plastics reinforced with glass fibers. These were the original (if not "advanced") modern composite materials that were used extensively in secondary (nonflight-critical) structures. Research eventually showed that these materials were not stiff enough to be used in primary (flight-critical) structures and that new fibers had to be developed. With respect to the first truly advanced composite material system (boron/epoxy), the Air Force took about fourteen years to change the status of boron/epoxy from an experimental material to a validated engineering material appropriate for use in primary aircraft structures. About five to seven years of further research and flight experience with demonstration articles and production hardware were needed to induce the airframe industry to commit substantial resources of their own to these materials.

In fact, the technology-development process may require budgetary commitments that extend far beyond the point of initial applications. For advanced composites, this commitment has lasted for about thirty years and will continue into the future as new types of composites and alternative manufacturing techniques are considered.

With respect to how the technology-development process for advanced composites might have been improved, this study finds:

- The manufacturing challenges associated with advanced composites might have been more strongly addressed earlier in the development cycle.

Perhaps the most important disincentive for using advanced composites is that manufacturing costs have always been significantly higher (a factor of two has not been uncommon) than those of traditional metals such as aluminum. In part, this is a lasting consequence of the low volumes that are typically associated with combat aircraft production programs. However, the high cost of manufacturing with composites has also slowed the

growth of these materials in commercial aircraft designs, thereby reducing another source of development funding.

To some extent, military weapon systems may suffer as long as new technologies developed to achieve high performance are not cost competitive with alternative technologies that may be employed in cost-driven commercial products. Early attention to these manufacturing challenges may result in a swifter adoption of new technologies of particular military interest by the commercial markets.

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1. STUDY OBJECTIVES

There are numerous essential elements of an effective and evolving "aircraft design capability." Qualified design personnel, manufacturing and test facilities, technical management, and analytical support capabilities are among these elements. Another critical component in the design and development process is the timely maturation of important new aircraft technologies. If such technologies are not available and understood prior to the start of a new system, design quality may be seriously compromised and the performance of the system will suffer. Only with some understanding of this complex process can effective options be generated for maintaining aircraft design capabilities in the face of declining opportunities for production.

The objective of this case study was to better understand how new aircraft technologies are matured and then assimilated by design teams. Although this objective can be succinctly stated, the answers are complex and they, in turn, raise many questions of their own. In particular, we seek to gain some insight about the roles that the Air Force and other governmental agencies play in forecasting, initiating, guiding, and funding technologies that are perceived to be of future military importance.

The topic of advanced composite structures was chosen as a model for technology development. For the purposes of this study, "advanced composites" are defined as a particular and very small subset of reinforced plastic materials. Advanced composites are generally distinguished from other reinforced plastics by the use of high-stiffness and high-strength fibers. A syntheses of high-performance fibers and modern plastics results in a set of materials with the potential to greatly enhance performance and reduce weight in airframe structures.

Composites cannot be treated as "black metals."[1] Fundamentally, an advanced composite is a two-phase (fiber and plastic matrix) material which can be tailored to specific design requirements by controlling the alignments of the fibers with respect to the applied loads. By controlling the alignment of the fibers within each ply of the laminated structure, the potential to meet new types of design constraints is created. For example, the forward-

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[1]An expression that is occasionally applied to an advanced composite structure that has been engineered using design philosophies that are most appropriate for metallic materials. "Black metal" structures are often overdesigned (and therefore heavier than necessary) since metallic design approaches do not account for the orthotropic nature of composites; thus, such approaches miss the potential for structural optimization that is possible in a fiber-reinforced material. The color "black" refers to the color of typical graphite-based material systems.

swept wing of the X-29 technology demonstrator would not have been possible without the coupling between bending and twisting deformations that can be created in an advanced composite laminate. Such tailoring is not possible with single-phase metals since the mechanical properties are the same in all directions.

However, composites are not without drawbacks of their own. For example, the relative weakness of the plastic matrix material binding the plies together often results in composite structures that can be easily damaged by unanticipated loads which are not taken by the fibers. Also, because composites are two-phase materials (each with different properties) and because the fiber alignments change through the thickness of the structure, warping and damage due to thermal stresses can occur during the manufacturing process. Although truly advanced composites have existed for about twenty-five years, the technical and operational communities are still striving to understand their unique characteristics in order to exploit their advantages and guard against their weaknesses. Thus, using these materials requires that new approaches to the design, analysis, and manufacturing of combat aircraft be developed.

The choice of advanced composite structural materials as a topic for a study of technology development was made for several reasons:

- Advanced composites are a pivotal technology in terms of both current and future aircraft performance.
- Composites are fundamentally different and more complex than metals.
- Composites are often considered to have a high degree of risk to both cost and schedule.

The first bullet addresses the fact that applications for composites are still expanding rapidly. For those aircraft where high performance is required, advanced composites are particularly important if not essential. The second bullet acknowledges the very different natures of composites and metals. It also implies that the analytical, design, and manufacturing techniques associated with composites are changing rapidly and that metals-related technologies may have little relevance to composites. The last bullet speaks to an enduring concern with composites: risk. Industry's experience with these materials, particularly at the usage levels that are envisioned for the next generation of combat aircraft, is very limited when compared with metals.

Some key questions for this technology-development study include:

- What roles have the Air Force (and other government agencies) played in the development of advanced composites?
- Through which mechanisms has this technology been transferred to weapon system designs?
- Approximately how much time was required for development?
- How much funding was required to develop advanced composites to the point of incorporation into a new weapon system design? What were the sources of funding?
- How did industry respond to this new and relatively risky technology?

Although the answers to such questions are very likely to be technology-dependent, we hope to be able to identify common factors which may be applicable to the evolution of future technologies that will be important in aircraft design.

The remainder of this Note is organized as follows:

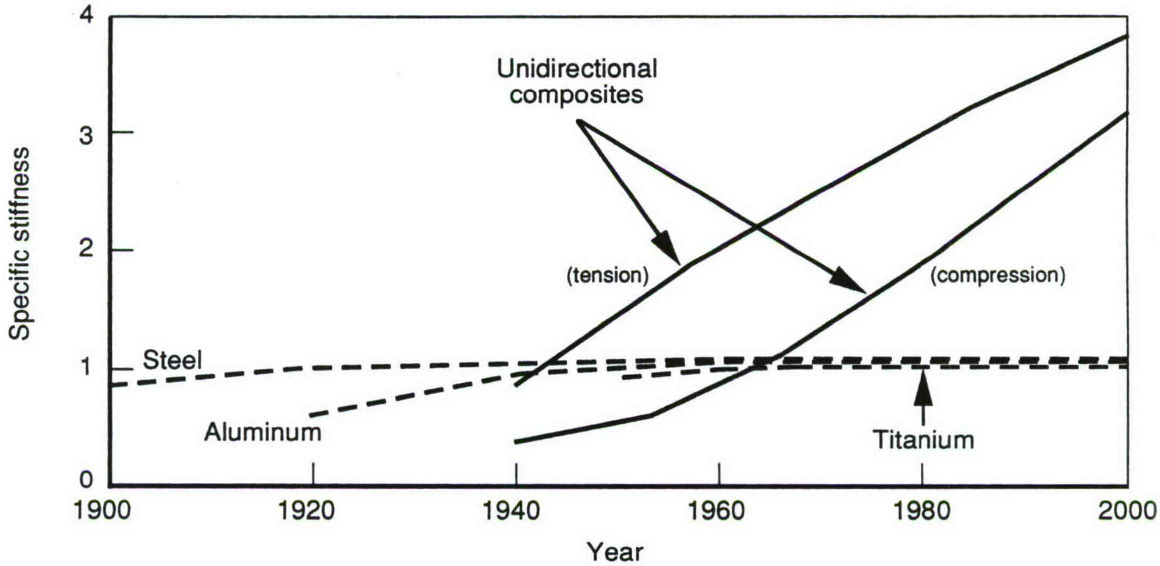
- Section 2: Plastics in aviation history. The reader is introduced to the general history of plastics in aviation. Although somewhat lengthy, such background information puts the development of advanced composites for combat aircraft into the proper context; that is, the continual search for advanced materials which can offer potential technological advantages in weapon systems. The history is examined by decade starting in 1940 and ending in 1989.
- Section 3: The roles of the Air Force.
- Section 4: The roles of other institutions.
- Section 5: Funding for advanced composites development.
- Section 6: Conclusions.

2. A TIMELINE OF PLASTICS AND FIBER-REINFORCED COMPOSITES IN AVIATION

BACKGROUND

This section provides a quick overview of the development of plastics and advanced composites in U.S. military aircraft. Motivations, technical achievements, and important players are discussed. The information is intended as general background material for the sections that follow but is not meant to be an exhaustive, technical treatise on composites. The following subsections are divided into a series of ten-year timeframes from the 1940s to the present. The highlights that relate to the development of composites are discussed.

The primary reason for the growing military interest in advanced fiber-reinforced composites can be demonstrated by plotting the increasing "performance" (here, material stiffness has been chosen) of these materials over time and then comparing the trends to the more conventional aerospace metals (Fig. 1). The trends in "specific stiffnesses" (stiffness of



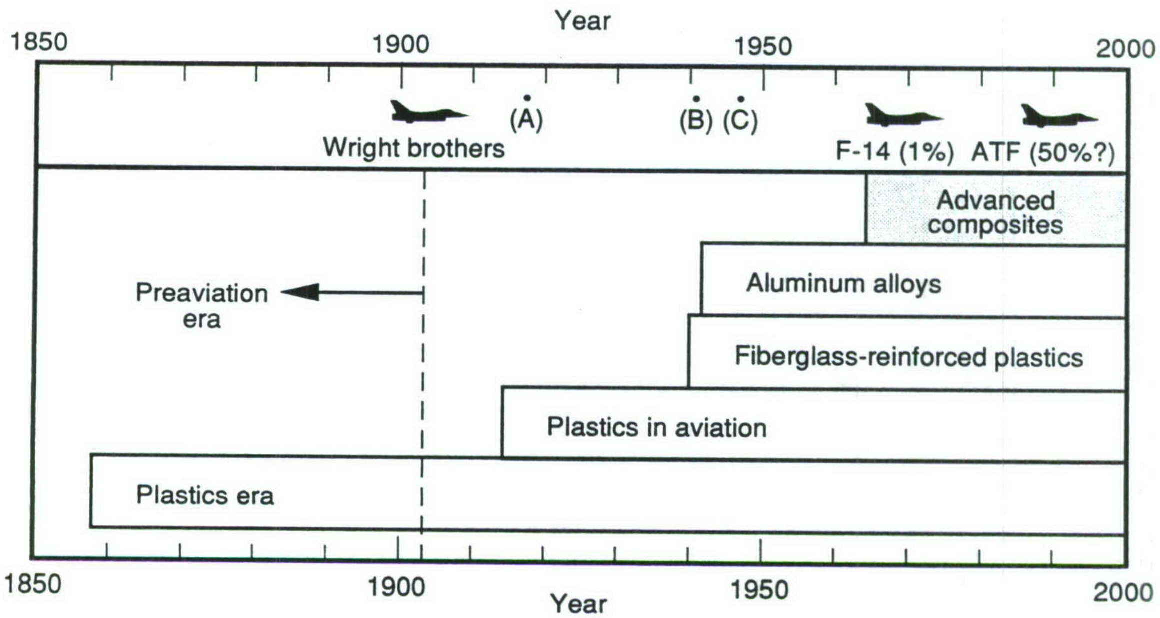
SOURCES: George Lubin (ed.), *Handbook of Composites*, Van Nostrand Reinhold, New York, 1982, p. 2, and David L. Grimes, *Trends and Applications of Structural Composite Materials*, North Atlantic Treaty Organization (NATO), Advisory Group for Aerospace Research and Development (AGARD), Report 523, presented at 21st meeting of the Structures and Materials Panel of AGARD, Nancy, France, November 17, 1965, p. 16.

Figure 1—Performance Trends in Airframe Structural Materials

the material divided by its density) for metals and unidirectional[1] composites at room temperature are compared. Clearly, key performance properties of advanced composites are still increasing rapidly while those of conventional metals have reached their peak.

Practically speaking, the use of advanced composites has resulted in weight savings as high as 30 percent relative to "equivalent" metallic metals combat-aircraft structures. It should be noted that the composite properties that are charted from the early 1940s to the mid-1960s reflect each material system that was reinforced with fiberglass. These systems are not considered to be "advanced" composites (where reinforcement is provided by boron or graphite fibers).

Figure 2 is a greatly simplified timeline that charts the major eras in the development of plastics and composites. The beginning of the modern era of advanced composites occurred relatively recently (about 1965). But in many respects, advanced composites are an



(A) Griffith experiment shows high strength of thin, perfect glass fibers and the drastic reductions in strength that occur due to small surface flaws.
(B) Airborne radar demonstration
(C) Supersonic flight

Figure 2—Plastics and Advanced Composites in Military Aviation

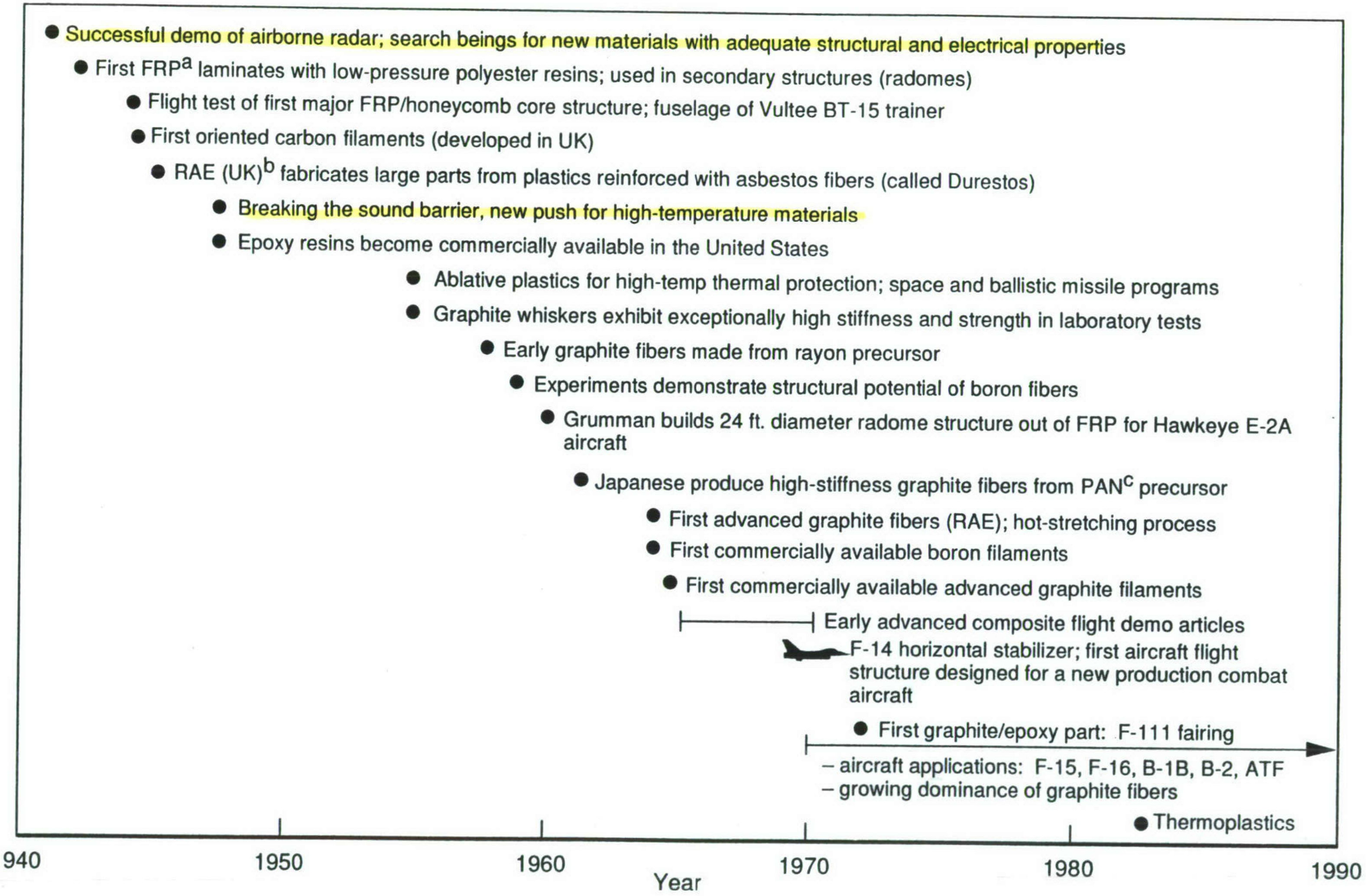
[1]"Unidirectional" composites refer to a very specific type of test specimen where all of the fibers are aligned in the direction of a single load. In practical designs, the loads are often multi-dimensional and thus advanced composite structures are optimized by varying the angle of fiber placement through the thickness of the laminate.

outgrowth of many years of earlier research with fiberglass materials. The year 1965 has been subjectively chosen to mark the start of modern composites research because the first commercially-available material systems based on these fibers did not appear until about 1965. Thus, broad-based research and development (R&D) programs that sought to apply advanced composites to combat aircraft systems did not begin until that time.

A timeline of some, but certainly not all, important technical milestones is shown in Fig. 3. Many of these milestones are directly related to the development of composites but others, such as the demonstrations of airborne radar and supersonic flight, are not. Even these seemingly "non-materials" events affected the course of advanced materials development. For example, the use of radar in radome structures required that materials be developed with traditional structural properties (e.g., stiffness, strength, resistance to corrosion and erosion) AND radar-compatible electrical properties. In another example, the thermal rigors of sustained supersonic flight meant that materials with higher temperature capabilities than aluminum would have to be developed. These situations illustrate that different types of technologies can exert pressure on each other through the medium of a complex weapon system. The items in Fig. 3 are discussed in more detail below.

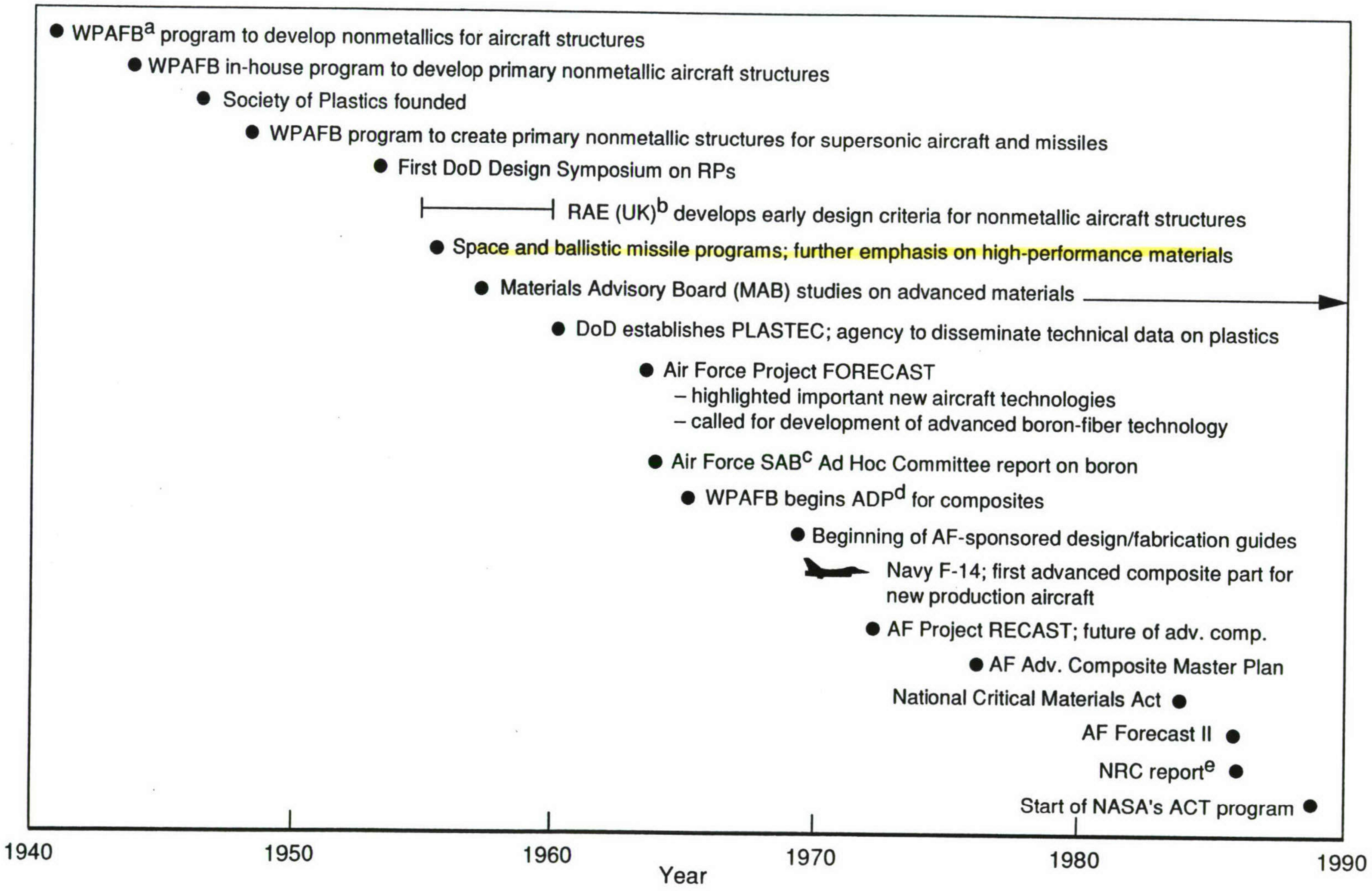
Institutional factors were also important in the development of composites (Fig. 4). In the context of this study, an institutional factor is broadly defined. For example, the emerging ballistic missile and space programs of the 1950s and 1960s, which put renewed emphasis on the development of all forms of advanced materials are institutional factors. Other factors are important organizations (e.g., the Materials Laboratory at Wright-Patterson AFB); still other institutional factors may be technology-forecasting exercises (e.g., Air Force Project FORECAST, which is explained in Section 3); or "roadmapping" efforts performed by such agencies as the Materials Advisory Board. Again, these items are discussed in more detail below.

Figure 5 illustrates the incorporation of composites into military aircraft as measured by the percentage of structural weight that is accounted for by advanced composites. The solid line differentiates the Air Force systems from those of the Navy (AV-8B, F-18); when this distinction is made, the sudden increase in the use of composites in Air Force systems becomes more apparent.



[a]FRP: fiberglass-reinforced plastic
[b]RAE: Royal Aircraft Establishment (UK)
[c]PAN: Polyacrylonitrile; important precursor for graphite fibers

Figure 3—A Timeline of Technical Milestones



[a] WPAFB: Wright-Patterson Air Force Base
[b] RAE: Royal Aircraft Establishment (UK)
[c] SAB: Scientific Advisory Board
[d] ADP: Advanced Development Program (for composites technology)
[e] Advanced Organic Composite Materials for Aircraft Structures—Future Program

Figure 4—A Timeline of Institutional Factors

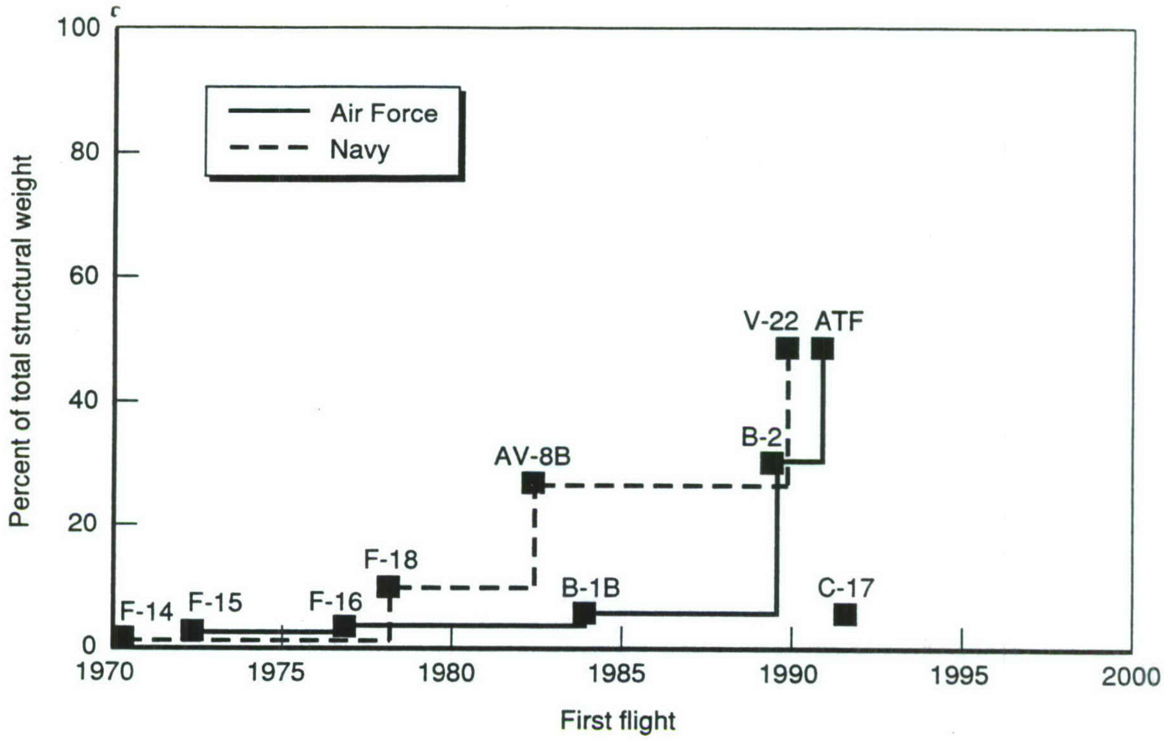


Figure 5—Trend of Composites Usage in Military Aircraft

PLASTICS PRIOR TO 1940

The earliest theoretical and experimental work in plastics began in the second half of the nineteenth century.[2] The growth of plastics in the early part of the twentieth century was largely motivated by the need for better insulators in the new radio industry and not by perceived inadequacies in the structural materials of the time. By 1920, molded and laminated plastics were established in a number of commercial industries, including: furniture, electrical insulators (for the radio industry) as well as airplane parts such as pulleys, cable guides, and laminated propellers. Some of these applications involved pure plastics while others added a reinforcing agent (such as fabric).

Research into commercial and military applications of plastics continued in the 1920s and 1930s. By the end of the 1930s, several factors led to an interest by the military in developing nonmetallic airframe materials using reinforced plastics. These included:

[2]R. B. Seymour and G. S. Kirshenbaum (eds.), *High Performance Polymers: Their Origin and Development,* Proceedings of the Symposium on the History of High Performance Polymers held in New York, April 15–18, 1986, Elsevier Science Publishing Company, New York, 1986, p. 9.

- the successful incorporation of plastics in lightly loaded secondary structures (e.g., instrument panels, nose sections, cockpit enclosures);
- the production of strong and light glass fibers by Owens-Corning;
- the production of matrix materials with the potential to meet military specifications;
- the concept of laminated structural forms.

These technical achievements and the political imperatives of World War II created a strong interest in superior military hardware and set the stage for the advanced materials research that began in the 1940s.

1940–1949

The decade of the 1940s was the real starting point for military R&D in nonmetallic airframe materials. In fact, the concept of reinforced plastic parts was already taking hold in the United Kingdom. For example, in 1937 the Royal Aircraft Establishment (RAE) flew airframe components fabricated from a phenolic resin reinforced with natural flax fibers.[3]

In the United States, the strong push for the development of new, nonmetallic materials for military use began in 1940. In 1941, Wright-Patterson Air Force Base (WPAFB) in Dayton, Ohio, was directed by General H. H. ("Hap") Arnold, then the Commanding General of the U.S. Army Air Forces, to investigate the full range of the potential applications of plastics to military aircraft.[4] This marks the beginning of the Laboratory's contribution to the development of advanced composite materials for military aircraft. The successful demonstration of airborne radar in 1941 was a very important factor in the development of nonmetallic materials. Such materials were necessary to design and manufacture radomes that were both structurally adequate (for small loads) and electrically transparent to radar.

WPAFB became interested in the application of reinforced plastics to lightly loaded, electrically transparent radomes[5] and also to highly-loaded structures so that very low-weight aircraft could eventually be produced (see Fig. 4, line 2). The Materials Laboratory at WPAFB became the R&D focal point for advanced materials development and structures

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[3]J. E. Gordon, *The Science of Structures and Materials,* Scientific American Books, New York, 1988, p. 187.

[4]George Lubin (ed.), *Handbook of Composites*, Van Nostrand Reinhold, New York, 1982, p. 9.

[5]J. E. Gordon noted that, "Radomes made in this way went into service around 1942 and had quite an important influence on the progress of World War II," in Gordon, p. 188.

research. Throughout the 1940s, this organization funded much of the development of advanced materials and their applications to flight structures.

The R&D work at that time centered around fiberglass as a reinforcement. These fibers were light, resistant to metal-damaging corrosion, very strong, and had already appeared in commercial applications. As mentioned earlier, fiberglass-reinforced plastics (FRPs) were particularly suited to radome applications since such fiberglass structures were transparent to radar and the radomes themselves did not carry high structural loads. Thus, fiberglass was the basis of the first modern (if not "advanced") composite material to be used in secondary structures and radomes were among the first FRP parts to be placed into production. Enormous experience[6] with FRP production parts (some quite large),[7] was gained over the next twenty years.

The problem with fiberglass was that it was not stiff enough. Primary aircraft structures tend to be stiffness critical.[8] The Materials Laboratory continued to experiment with both primary and secondary fiberglass structures for many years but it was found that the stiffness of the material was indeed too low and that primary FRP parts could not be considered for production of combat aircraft.

The realization that fiberglass was unsuitable for critical structural applications spurred the research into new fiber materials which eventually led to the advanced composites. The experience that was gained, both by industry and by the Materials Laboratory, with FRP parts was important for the technology development of the advanced composite materials that began to appear in the early 1960s. However, industry did not gain experience in the design, manufacturing, and testing of primary composite structures. This lack of experience with primary structures also meant that much effort would have to be devoted to materials qualification, screening, structural testing, failure analysis, etc.

Supersonic flight also affected advanced materials research. While the increase in structural temperatures due to aerodynamic heating at Mach 1[9] is relatively small, there is a rise in local skin temperature as the Mach number is further increased. At Mach 2, localized temperatures are on the order of 250F; at Mach 3, temperatures may reach 650F. Thus, unprotected aluminum structures are limited to Mach 2 conditions of short duration. New

[6]A. Lovelace, "Advanced Composites," *Journal of Aircraft,* Vol. 11, No. 9, September 1974, p. 503.

[7]In 1960, Grumman Aerospace produced a fiberglass radome structure 24 feet in diameter for the Hawkeye E-2A aircraft.

[8]During this time, the concept of honeycomb-core sandwich structures was developed to help increase the stiffness of airframe structures. Sandwich structures are still an integral part of the design process and are often used with advanced composite laminates.

[9]Flight at Mach 1 was first achieved in October 1947.

materials capable of withstanding these temperatures needed to be developed if sustained supersonic flight was to become a reality. Prior to supersonic flight, design service temperatures were dictated by the ambient environment (not aerodynamic heating) and were on the order of 160F.

1950–1959

A great deal of research in advanced materials during the 1950s was motivated by the ballistic missile and space programs as well as the increasing interest in supersonic flight. These programs opened up entirely new operating regimes and environmental conditions. Conventional structural materials such as aluminum were viewed by the technical and defense communities as insufficient to support these new design requirements.[10] Research into all possible types of advanced materials (e.g., reinforced plastics, high-strength refractory metals, ceramics, polymers) was called for at the highest levels of government.[11] With respect to advanced fibers, materials with low molecular weights on the periodic table (e.g., boron, beryllium, silicon, and carbon) began to be examined as possible replacements for fiberglass which had been found to be insufficiently stiff. Through Air Force-sponsored research, boron[12] emerged as the first of the advanced, high-stiffness, high-strength fibers, although carbon was also being researched. In an attempt to raise material-operating temperatures, the Materials Laboratory also began R&D programs on metal-matrix and ceramic-matrix composites. In fact, these areas of composites research have proceeded slowly[13] and are only now beginning to find airframe applications.

Research also verified the difficulty of translating the very fine, nearly perfect properties of whiskers[14] produced in the laboratory to the bulk forms necessary to fabricate real structures. As early as 1918,[15] A. A. Griffith[16] had illustrated the tremendous reductions in strength that could occur as a result of small amounts of surface damage to

[10]Air vehicles with speeds of Mach 4–6 (with localized skin temperatures of up to 2000 degrees Fahrenheit) were envisioned for the future.

[11]National Academy of Sciences/National Research Council, Committee on the Status and Viability of Composite Materials for Aircraft Structures, *Advanced Organic Composite Materials for Aircraft Structures–Future Program,* Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems, National Academy Press, Washington, D.C., 1960, p. vii.

[12]In fact, boron fibers are actually boron coatings surrounding a tungsten core.

[13]Aside from low levels of funding, technical difficulties included: the brittle nature of ceramics (undesirable in a structural material), and fiber/matrix interface problems which are difficult to solve and have a large effect on the characteristics of the composite.

[14]Whiskers are thin, hairlike crystals grown from a solution or vapor.

[15]Gordon, p. 188.

[16]A. A. Griffith (1893–1963) developed a revolutionary theory on the strength and fracture of solids. Griffith published his theory in 1920 while working at the Royal Aircraft Establishment in Farnborough, England.

perfect whiskers and fibers. Thus, development of surface coatings to protect fibers during processing became important.[17] The relationship between fiber with diameter and continuous length and its effect on measurable strength was explored. The optimum condition for structural materials was long, continuous fibers with very small diameters.

Although no single country was responsible for the maturation of carbon fiber technology, the United Kingdom seems to have started first. The development of applications for carbon fibers for aeronautical use was almost exclusively financed by military and space agencies in the United States and the United Kingdom. During the mid-1950s, the United Kingdom also gained considerable design experience with composite parts. In Japan, early research into carbon (graphite) fibers appears to have been motivated by potential applications in commercial markets.

1960–1969

The first half of this decade culminated in the commercial availability of the first truly advanced composite material system while the latter half was distinguished by intense effort to develop flight structures. The development of boron/epoxy was accelerated in the early 1960s after the Air Force's Project FORECAST study highlighted this material as an important new technology. Again, it should be remembered that the Air Force's enthusiasm for new materials was motivated by a growing realization (since the late 1950s) that then-conventional materials would not meet the requirements of supersonic and space flight for manned and unmanned systems. Although boron was eventually replaced[18] by high-stiffness, high-strength graphite material systems (which became cheaper to produce and easier to work with) during the 1970s, boron/epoxy served to initiate the development of advanced composite flight structures.

An important institutional force that contributed to the early development of composites was the Air Force's Project FORECAST (1963). Project FORECAST highlighted the potential structural benefits of boron composites. General Bernard A. Schriever, head of the study, acted as a technology advocate within the Air Force and was instrumental in attracting the necessary research funding to produce a commercially available material system.

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[17]Development of organic coatings allowed glass fibers to be spun and woven like other fibers without losing too much strength. More modern research on coatings has been directed towards the problems of fiber-oxidation and undesirable interactions with the matrix.

[18]Boron/epoxy is still finding occasional uses: e.g., as a long stiffener in the fuselage of the B-1B.

Another critical institutional factor was the Advanced Development Program (ADP, see Fig. 4) within the Air Force Materials Laboratory. Once the materials were available, the ADP[19] was used to fund research in the development of composite flight structures in military aircraft; primarily through the replacement of existing metal structures with composite alternatives. The main goals of the ADP program were: (1) to encourage the rapid application of the new materials technology to military airframe structures and, (2) to foster long-term, advanced materials capabilities within an airframe industry that had experience with secondary fiberglass structures but little or none with primary, nonmetallic aircraft structures.

The initial technical goal of the program was to fund industry to design, manufacture, and test (ground and flight) advanced composite replacements for existing metallic flight structures. The intent was to start with less critical components and then to proceed to more flight-critical structures as experience was gained. Metal components were evaluated with respect to their potential to be replaced by a composite design.[20] Some significant weight savings were achieved and valuable experience was gained. But the airframe industry, which was well versed in producing metallic structures, viewed advanced composites with considerable risk. While the "primes" (primary contractors in the aviation industry) were certainly interested in advancing the state of the art in composites via R&D funding, they were less willing to commit themselves in terms of proposals for new designs (e.g., the lightweight fighter program). By the end of the decade, there were only a handful of boron/epoxy components in service. However, the number of advanced composite parts in military service increased dramatically in the 1970s. The Navy's need for weight reduction presented the first opportunity to produce an original composite structure for a new aircraft, the F-14 boron/epoxy horizontal stabilizer. USAF funding (through the ADP) was used in the development of this part.

The growing involvement of academic institutions in composites research was another important institutional factor of the 1960s. One source[21] who was closely associated with the Air Force composites program, believed that if academicians became interested in the technology, they would begin teaching it to their students. The goal was to educate a new

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[19]ADP started in 1965.

[20]Programs in the first year included: a composite F-111 stabilizer, helicopter rotor blades (Boeing/Vertol), applications to reentry vehicles (General Electric), and a basic materials program that was intended to supply raw materials to the other programs.

[21]Personal communication with Dr. Alan Lovelace, Chairman (Commercial Launch Subsidiary), General Dynamics, San Diego, Calif., November 1990.

generation of structural engineers who thought in terms of "anisotropic," not "isotropic"[22] material behavior. Earlier guidance (late 1950s) from technical committees within the National Academy of Sciences/National Research Council (NAS/NRC) had also been stressing the importance of academic participation; in their view, universities had a dual role: to perform basic research (including theoretical development) and to educate students in the most recent technological advances. Academic involvement as measured by university facilities and research programs in composites, increased rapidly in the 1970s and 1980s.

Elsewhere in the world, the United Kingdom (1964) produced the first true high-modulus graphite[23] fibers using the "stress-graphitization" technique.[24] High-stiffness and high-strength graphite fibers started to become commercially available around 1967. Japan performed extensive research in the producibility of graphite materials. As a result of this research, Japan became a major supplier of advanced graphite fibers to the United States by the end of the decade.

In summary, the very early stages of development work in composites were completed in the 1960s. Enough experience was gained to at least start the process of designing new aircraft structures with composites. However, there was still much to do to develop new manufacturing capabilities and facilities. Design experience was still very limited; as were the numbers of qualified design personnel. Both boron and graphite/epoxy material systems had become available to the airframe industry.

1970–1979

The application of advanced composites to the production of military aircraft really began in the early 1970s. In terms of structural weight (Fig. 5), the maximum percentage of composites for any combat aircraft produced in that decade was about 10 percent for the Navy (F-18) and less than 3 percent for the Air Force (F-16). One source[25] estimated that about 500 composite structures (both boron and graphite/epoxy) were in service on military airframes by 1975, increasing to nearly 3000 parts (total) by 1980; on such military aircraft as the F-14, F-15, F-16, F-18, as well as the A-7, F-111, F-4, and C-5A transport. By 1975,

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[22]Isotropic behavior is exhibited by metals; the relative homogeneity of metals results in a set of mechanical properties that are constant in all directions. Anisotropic behavior is found in composite structures; the mechancial properties are highly dependent on the orientation of the reinforcing fibers.

[23]The terms "carbon" and "graphite" fibers are often used interchangeably by structural designers and engineers.

[24]Research had indicated that high mechanical properties were achieved when the precursor fibers were pyrolyzed while being stretched.

[25]USAF Scientific Advisory Board, *Report of the Ad Hoc Committee on Advanced Composites Technology,* DRAFT COPY, September 1976, p. 7.

graphite had become the fiber of choice (over boron) because of lower raw material costs (by the late 1970s, about 40 dollars per pound versus 180 for boron) and ease of fabrication.

The prime airframe contractors became increasingly convinced that advanced composites were going to play a fundamental and enduring role in the industry. Starting around 1975, the industry began to make its own commitments to the technology by investing in and constructing dedicated composites facilities. Perhaps this was the result of a few years worth of relatively successful flight experience with advanced composite parts and the realization that these structures could function effectively. This investment was also a consequence of the perceived long-term commitment by the services to using advanced composites. However, the general level of manufacturing technology was still low.

National Aeronautics and Space Administration (NASA)-funded R&D programs aimed at incorporating composites into large commercial-transport aircraft. In part, these efforts were motivated by belief that acceptance and use by the commercial airframe producers would lower the costs of using composites. Also, exports of commercial aircraft have always been very important to the U.S. economy; therefore, another motivation for incorporating composites into these transports was to maintain a qualitative edge over potential competitors. Success in this objective has been slow.[26] NASA has recently begun again to pour large amounts of money into research designed to reduce the costs of composites and to make them more attractive to commercial aircraft producers.

High-level attempts to roadmap the assimilation of composites into both military and commercial applications continued in the 1970s. The main goals of these efforts were to decrease manufacturing costs associated with composites while increasing confidence. As mentioned above, acceptance of advanced composites by the commercial industry has been slow because of that industry's emphasis on lower cost.

By the end of the decade, utilization of composites in military aircraft was still hindered by a number of factors: unknown operation/maintenance costs, uncertainties with respect to production costs and schedules, uncertainties as to how the safety/durability of composite structures should be defined and tested, environmental concerns (e.g., tendency for epoxies to absorb moisture over time), minimal standardization (each aerospace company developed its own specifications which resulted in duplicative [and expensive] material characterization efforts), large variations in composites capabilities between companies, and a lack of qualified design, engineering, and manufacturing personnel. Many of these

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[26]One source estimates that current usage of advanced composites in commercial transports is about 3–7 percent of structural weight (as compared to military aircraft of the 1980s and 1990s which presently contain 5–50 percent composites). See Walcoff & Associates, Inc., *Polymar Matrix Composites Research: A Survey of Federally Sponsored Programs,* DOE/ER/30152T-H1, June 1990, p. D-4.

concerns could be adequately addressed only through production experience and service testing.

1980–1989

The decade of the 1980s was marked by more technical advances in composites technology and fairly aggressive strategies for application. Composites were flown on new aircraft such as the AV-8B, B-1B, and B-2; composite aircraft still in development included the Advanced Tactical Fighter (ATF), the C-17 transport, and the V-22. The percentages of advanced composites on these aircraft probably range from 5 percent to nearly 50 percent, considerably higher than in the previous decade. Composites were used in both primary and secondary structures and in substructural elements[27] as well as in skin panels. It should be noted that the B-1B and perhaps the F-117 were the only new Air Force aircraft of the decade which generated production experience with composites.

One of the most significant materials-related developments of the 1980s was thermoplastic resins with the potential to be suitable partners for advanced fibers.[28] Thermoplastics, unlike traditional thermosetting epoxies, are theoretically reformable and require much shorter consolidation times than epoxies, but they also require higher consolidation temperatures. The short consolidation times (minutes for thermoplastics versus hours for thermosets) and reformability could lead to significantly lower manufacturing costs, particularly if suitable manufacturing techniques can be developed that avoid the traditional use of expensive autoclave curing techniques. Thermoplastics also have better damage tolerance and are relatively immune to the shelf-life constraints that are associated with thermosets.[29] Experimental components such as skin panels began flight testing in the late 1980s. The earliest production application for fiber-reinforced thermoplastics on a new combat aircraft may be the ATF.

Thermoplastics represent not only an important technical achievement, but also a change in the technology and development process as well. This process has been criticized for being very lengthy and one source discusses how the development of thermoplastics may be differing in this respect. According to the source:[30] "In traditional materials development,

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[27]Such as the sine-wave spar on the AV-8B.

[28]National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, *The Place for Thermoplastic Composites in Structural Components*, NMAB-434, National Academy Press, 1987, p. 1. In 1983, polyetheretherketone (PEEK) was developed; this thermoplastic resin was the first to be developed with sufficient solvent resistance to be considered for use in aircraft applications.

[29]Thermosets generally require refrigeration and have a limited shelf-life (6–12 months).

[30]National Materials Advisory Board, 1987, p. 1.

experience was first gained with the production of small parts in secondary structures before any major commitment was contemplated. However, in the current era of rapid technological development, new material systems and further innovations are brought rapidly from introduction to application. This rapid development has precluded generation of a broad base of experience in a variety of applications. At the same time, a detailed science base for thermoplastic composites has not been developed." Time will tell if thermoplastics live up to expectations and if the strategy of more rapid introduction was well conceived.

Work continued on metal-matrix (MMC) and ceramic-matrix composites (CMC). Some testing was performed on MMC aircraft parts; production applications will not occur before the 1990s and possibly not until after the turn of the century.

Designers were attempting to create larger and more integrated composite airframes. This change was motivated by the belief that fabrication costs could be decreased if the total number of parts and assembly operations in a design were reduced. It was also felt that fewer attachment points and fastener holes would reduce the potential number of damage initiation sites and thus enhance the reliability of the aircraft. The practical limit of designing larger, more integrated structures (and its effect on repairability) has yet to be determined. The cost of manufacturing composite structures was still significantly higher than metals.

Increasing requirements for low-observability (stealth) is another factor affecting the application of composites in at least some of the aircraft produced in this decade. Although details in this area are tightly held by the Air Force, the available information seems to suggest that advanced airframes will be required to meet both structural and electrical specifications. This is another new area for composites which is bound to affect the design and manufacturing processes.

The general level of manufacturing technology increased significantly, but still remained on the low side given the new materials and larger, more integrated, stealthier structures that are being considered. Significant investments were made in large, automated tape-laying machines, large autoclaves, computer-controlled curing and machining processes, and advanced inspection devices.

Other noteworthy activities relating to the development of advanced composites during this decade include:

- renewed efforts to incorporate composites into commercial transport aircraft;
- government-mandated goals for domestic fiber production;
- the increasing roles of advanced materials associations.

Much of this work is being conducted by NASA through the Advanced Composites Technology (ACT) program. The magnitude of this effort is large: about $140 million over six years (ending in 1994). Two projects that are aimed at developing composites technology for wing and fuselage structures have total contract values of $22 and $24 million (conducted by Lockheed and Boeing, respectively). Specific areas of interest include: thermoplastic forming techniques, laminate stitching, manufacturing technologies for heavily loaded structures.

A new law[31] was passed that required (by 1992) at least 50 percent of annual DoD carbon fiber requirements be manufactured from domestically sourced polyacrylonitrile (PAN) precursors.[32]

SACMA[33] represents an attempt by advanced materials companies to unite under a common banner in order to more effectively carry out lobbying activities. SACMA briefs the Congress on the state of the advanced materials industry, and interacts with other associations (such as the Aerospace Industries Association) for the purpose of developing technology roadmaps that represent an industry point of view. These groups are attempting to integrate commercial and defense technology objectives in order to present more integrated strategies for advanced materials development. They are concerned with changing the way the government administers its R&D programs, and they promote changes in data and intellectual property rights, investment tax credits, etc.

In the broadest sense, the decade of the 1980s saw the issue of advanced materials technology mature into something much larger than a specialty area within the Department of Defense. Much thought and money began to be used to address one fundamental question: How can advanced composites be made more attractive to commercial industries?

With respect to composites on combat aircraft, production continued on several 1970-vintage systems: F-14, F-18, AV-8B, F-15, F-16. Production of two new Air Force systems

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[31]Section 8088, Public Law 100–102.

[32]PAN precursor fibers are processed (pyrolyzed at very high temperatures) to produce carbon fibers.

[33]The Suppliers of Advanced Composite Materials Association (SACMA) has over 70 regular, associate, and affiliate members, which include material suppliers, companies which produce composite structures, universities, trade magazines, etc. Their members include such organizations as Dow Chemical, CIBA-GEIGY, Dupont, Hexcel Corp., Owens-Corning, University of Delaware, SAMPE, Composites Horizons, Advanced Composites Magazine, etc.

began: B-1B and F-117. Development began on such new systems as the C-17, B-2, ATF, and A-12. Manufacturing capabilities generally increased, but so did the requirements and complexity of new aircraft designs. New types of composites, each with their own eccentricities, also began to emerge: thermoplastics, metal-matrix composites, ceramic-matrix composites, and bismaleimide and polyimide thermosetting epoxies. There was also a strong increase in the number of specialty companies dealing with all aspects of composites: materials research, design and manufacturing of commercial and defense components, suppliers of analytical services, etc.

3. THE ROLES OF THE AIR FORCE

The Air Force has been actively involved with the development of nonmetallic materials for aircraft applications since 1940. Throughout the 1940s and 1950s, fiber-reinforced composites such as fiberglass/polyesters and fiberglass/epoxies were qualified for use only in secondary airframe structures. However, as shown in Fig. 4, the new flight regimes (e.g., supersonic, space) that began to open up in the middle to late 1950s motivated the government and DoD to reassess the adequacy of then-standard structural materials, and to think about how advanced materials could be developed more quickly. This is the context in which the Air Force's initial search for advanced composite materials began.

Since that time, the roles that the Air Force has played in the development of advanced composites technology could be very generally categorized as follows (in an approximate chronological order):

- Identifying a potentially important new technology;
- Fostering advanced composite materials development;
- Fostering design and manufacturing capabilities within the airframe industry for advanced composites.

The first bullet reflects the fact that Air Force efforts at identifying critical technologies with potential military applications played an important role in the early identification (and focus of resources) on advanced fibers such as boron and graphite. A number of people associated with the Materials Laboratory at Wright-Patterson AFB stated that the research emphasis in the early 1960s was on materials development. They felt that the issues of specific applications, fabrication techniques, producibility, etc. (about which they had many unanswered questions) could only be addressed once the material systems were available in meaningful quantities. This is not to say that these scientists and engineers did not consider "post-materials-development" issues worthy of study; rather, they believed that the first priority of the Materials Laboratory was to make promising material systems available to the airframe industry as quickly as possible. Design, testing, and application of composites to flight structures (as well as the development of manufacturing capabilities within the industry) were the focus of the Advanced Development Program that began in 1965.

The second bullet acknowledges that several years (about five) of research in materials development were necessary after identification of the technology in order to produce a commercially-available, advanced composite material.

The third bullet indicates that the relatively quick development of initial applications of advanced composites technology (once initial materials were available) to flight structures was very much a consequence of the commitment by Air Force technology organizations. An important result of this early work was the generation of an initial technical database from which the industry at large could draw. Given the relative expense of these materials, this was an important step in encouraging the industry to use advanced composites. Without the Air Force's early commitment to applying these materials to flight structures, it seems likely that the application of this technology to aircraft systems would have occurred much more slowly because of the risks to cost, performance, and schedule that were perceived by the airframe industry.

The Air Force performed other important functions as well. These included the dissemination of technical results through distribution of reports, interaction between industry and Air Force technology organizations, and sponsorship of technical seminars. Again, given the relative expense of the technology, it was important for the Air Force to distribute research results as widely as possible.

Another important role of the Air Force was to encourage academic involvement in advanced composites technology. This involvement served a dual purpose: to fund universities to perform basic research and to expose the next generation of scientists, designers, and engineers to this new technology. Given the relatively small amount of R&D money that was used for this purpose, the potential technological payoff (though difficult to quantify) seems quite large.

IDENTIFYING A POTENTIALLY IMPORTANT NEW TECHNOLOGY

Technology-forecasting efforts by the Air Force in the early 1960s stemmed from a conviction by government/DoD that science and technology were to have an increasing influence on strategic planning activities. In particular, the development of advanced materials was perceived as an enabling technology if the benefits of military supersonic and space flight were to be fully exploited.

In 1958, the National Academy of Sciences/National Resource Council (NAS/NRC) concluded that the complexities of new flight regimes warranted the development of all types of advanced materials (metallics and nonmetallics). NAS/NRC predicted that the Air Force would progressively encounter more difficulty in solving its materials problems because the

mechanical properties and characteristics necessary for supersonic flight would be well beyond the needs of the rest of the DoD and commercial markets. Thus, they concluded that the Air Force must accept responsibility for a substantial part of any national, advanced-materials development effort. NAS/NRC also claimed that in-house research by the Air Force could not match that of industry and that more research should be contracted out. NAS/NRC also believed that R&D budgets were too small to begin to address new materials needs. It is interesting to note that although these technical communities had clearly indicated the need for the development of new materials, the particular class of composite materials, while identified, was not at the top of their list of most promising candidates.

The technology forecasting efforts made by the Air Force differed from other higher-level studies in that they provided the service with a more direct forum to state their own views about which technologies may be important drivers in developing new combat capabilities to meet future threats. These studies have afforded the laboratories within the Air Force a chance to exercise the technical expertise they gained from their support of R&D by providing important feedback (e.g., from operational systems) to the forecasting effort. Through the forecasting studies, a certain closure is achieved; the laboratories fund R&D for a number of years in order to explore and develop potentially important technologies and then are periodically asked to exercise that knowledge by helping to assess future R&D priorities.

Project FORECAST

The Air Force conducted a technology-forecasting study, entitled Project FORECAST, from 1963 to 1964. The goal was to evaluate the military potential of science and technology, as related to Air Force requirements extending into the mid-1970s. The study involved about thirty separate Air Force organizations, about fifty other government agencies, and approximately eighty industry participants (both profit and nonprofit). Panel chairmen were a mix of Air Force and industry personnel.

The highest priority, according to the results of the study, was materials technology. Given the emerging demand for advanced materials R&D at the time, this was hardly a surprise.[1] In particular, the structural potential of boron fibers was greatly extolled. Although some of the potential benefits were perhaps stated a bit overzealously, the study

[1]Project FORECAST highlighted other technologies as well. These include: dispersion-hardening of metals to achieve high-temperature capabilities in engines, turbofan engines, hydrogen-fueled engines for Mach 6 flight, laminar flow control (for extended range), variable geometry wings (to allow efficient flight in varying regimes from high-speed penetration at low altitude to supersonic dash at high altitude), and boundary layer cooling.

had correctly identified the revolutionary potential of this class of materials. However, this realization stemmed, at least in part, from years of previous research with fiberglass composites and the failure of that material to meet the stiffness requirements for many primary aircraft structures.

The Air Force had been supporting research in boron fibers[2] for at least two years prior to the Project FORECAST final report. A development plan called for a decision point on boron production by 1968 and the availability of the material for general airframe use by 1970–1975. The Air Force recognized that this would be a major program requiring substantial amounts of money. In terms of timeframes, these predictions were quite accurate; the materials were available prior to 1968 and production aircraft parts fabricated from boron/epoxy began to appear in the early 1970s.

One source[3] discussed the role of General Bernard A. Schriever (director of Project FORECAST) as a technology advocate within the Air Force. Apparently, the Air Force's newly identified interest in boron fiber technology had its critics within the government. Schriever, according to the source, provided sufficient protection so that this research could go forward even though questions had been raised as to the viability and applicability of this particular technology. The implication is that Schriever's personal belief in the potential of the technology allowed the Air Force to pursue its interest in the development of advanced composites.

It is interesting to note that the FORECAST report made brief statements on the potential benefit of these advanced materials to civilian markets as well. However, widespread, volume-intensive applications of advanced materials in such civilian markets as the commercial aircraft and automobile industries will not likely be achieved prior to the mid- to late-1990s.[4]

Other Studies

The Air Force has periodically engaged in studies that have attempted to influence the development of composites.[5] One of the more recent studies, FORECAST II, was conducted in the mid-1980s. This study expended a great deal of effort trying to correlate emerging technologies with future requirements and advanced systems. In terms of conclusions about

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[2]In fact, the Air Force was originally interested in boron as an additive to fuel.

[3]Personal communication in April 1990 with Dr. Alan Lovelace, Chairman (Commercial Launch Subsidiary), General Dynamics, San Diego, Calif.

[4]Walcoff & Associates, Inc., p. D-4.

[5]SAB Ad Hoc Committee on Boron Research (1964); SAB Ad Hoc Committee on Filamentary Composites (1968); SAB Ad Hoc Committee on Advanced Composites (1971); RECAST (1972); Air Force Advanced Composites Master Plan (1976).

future research emphasis, composites also played a large role in FORECAST II. Topics in this area included: molecular composites, ordered polymers, high-temperature materials and ultra-lightweight composite structures. Development plans and funding levels were also proposed. Technical goals, timeframes and dollar amounts were defined in terms of R&D program elements 6.1, 6.2, 6.3, and 7.8 (manufacturing technology) for each technology.

Summary

Forecasting efforts did serve a useful purpose with respect to advanced composites technology. The original FORECAST was an important mechanism by which needed attention and resources were allocated to the development of boron fibers. The national importance of advanced materials development had already been stressed in higher-level technology-assessment studies, for example, the NAS/NRC that had been conducted in the years before FORECAST. Thus, the context of the FORECAST study had been set by prior national guidance; FORECAST succeeded in implementing that guidance by highlighting a new and potentially key materials technology. However, it appears that the Air Force's point of emphasis (boron fiber technology) was not without critics. The early identification and R&D support of composites are evidence of the utility of the Materials Laboratory in helping to determine Air Force research directions. In order to continue this process in the future, it seems likely that the laboratories need to be active and to support a wide range of projects if they are to keep the Air Force up to date on technologies with potential military benefit.

These studies also give the laboratories opportunities to use their technical expertise to influence future R&D priorities and technology development. The defense industry may also benefit in the sense that they get a clearer understanding of which technologies may be important in military markets. The collective knowledge of the laboratories can also act as an important sanity check on industry proposals and designs.

FOSTERING ADVANCED COMPOSITES MATERIALS DEVELOPMENT

Further development of the advanced materials themselves was necessary prior to application. From a historical perspective, the advanced materials of the present have their roots in the fiberglass-reinforced-plastics era of the 1940s and 1950s. The push for the development of nonmetallic structural materials with superior specific strengths for applications to military aircraft began in 1940. In 1941, General "Hap" Arnold directed Wright-Patterson Air Force Base to investigate the full range of the potential applications of plastics to military aircraft. By this time, both pure and reinforced plastics had already

found some airframe applications and it was clear that many commercial industries[6] were taking advantage of plastics. In fact, the concept of reinforcing plastics with fibers was already taking hold in the United Kingdom. For example, in 1937 the Royal Aircraft Establishment (RAE) flew components fabricated from a phenolic resin reinforced with natural flax fibers.

Glass fibers, which had been developed in the mid-1930s, were very strong, light, and resistant to corrosion. Thus, they were very attractive from a military point of view. During this time, the Air Force was the primary focal point for providing technical guidance and R&D funding to the materials and airframe industries. The Materials Laboratory sponsored many research efforts aimed at improving fiber geometries, mechanical properties, producibility, and matrix processing requirements, as well as funding the early attempts at large-scale applications of these materials to aircraft structures. Because the requirements for technical expertise and facilities were very specialized, it appears that the Materials Laboratory contracted out research centering on materials development. This is still the case today.

The Materials Laboratory sponsored research to help remove technical obstacles to industry use and acceptance of composites. For example, during the 1940s, the Materials Laboratory sponsored research on reducing the cure pressures required for plastic matrix materials.[7] Prior to 1942, high pressures (on the order of 2000 pounds per square inch) had to be applied during the cure of fiberglass-reinforced polyester materials in order to remove the volatile products that emerged from the matrix. By 1942, AFML funding had resulted in a fiberglass/polyester material system that could be cured with a low level of pressure (on the order of 300 psi). This new material system meant that the production of composite structures could be achieved with equipment that generated significantly lower pressures. Thus, an important inhibition to using and applying composites in the airframe industry was dramatically lessened. As in the area of fiber research, the Materials Laboratory continued to fund the development of matrix systems with better performance and manufacturing characteristics.

The development of fiber materials and properties was also part of the Laboratory's activities. The Materials Laboratory became interested in other materials during the mid- to late-1950s. The realization that fiberglass materials were not sufficiently stiff enough to support primary structural applications spurred the search for superior fiber materials. Research was performed on such materials as boron, carbon (graphite), and beryllium. In

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[6]Plastics were found in the radio industry, furniture business, even women's apparel.
[7]Lubin, p. 9.

1959, exploratory development funding was given to Texaco for work in boron.[8] Ultimately, the potential stiffness and strength of this material was demonstrated to the Air Force, and it was highlighted as a key emerging technology in the Project FORECAST effort (1963). This quickly led to the start of the advanced composites era around 1965.

In 1965, the Materials Laboratory supplied 6.2 development funding to Union Carbide to develop carbon fiber technology (which was also being developed in the United Kingdom and Japan).[9] According to one National Research Council report,[10] however, carbon fiber technology received much less federal funding in its early development than did boron. Thus, in terms of research funding, carbon fiber technology was a few years behind boron, but it quickly became clear (by about 1968) that carbon fibers could have significant advantages. In fact, boron was largely replaced by graphite by the mid-1970s, and boron has now been relegated to special design situations.

Some R&D topics in composites that were initially sponsored many years ago are only now maturing to the point where they can be considered for aircraft structures. For example, during the late 1950s, the Materials Laboratory supported the development of metal-matrix and ceramic-matrix composites. While they have been slow to mature, they offer very significant increases in service temperatures over traditional polymer matrix composites.

FOSTERING DESIGN AND MANUFACTURING CAPABILITIES WITH ADVANCED COMPOSITES

Research in Applications of Early Fiberglass Composites

In terms of in-house activities, Wright-Patterson was very much involved with the development of the first fiberglass-composite flight structures. Calculations made at AFML indicated that an efficient structure could be made from fiberglass-polyester laminates and a honeycomb core. The aft fuselage of the Vultee BT-15 trainer was selected as a candidate for redesign.[11] This structure was flown at Wright-Patterson in 1944, and it is considered the first major fiberglass-reinforced structural component to be developed and flight tested. In 1945, fiberglass laminate/honeycomb core wings for the AT-6 aircraft were fabricated at Wright-Patterson. This structure was eventually flight-tested in 1953.

While such design and manufacturing exercises proved to be relatively successful as demonstrations, it became clear that fiberglass was not stiff enough to be considered for

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[8]Personal communication with G. Peterson (head of the Air Force's Composites ADP program during the 1960s), Dayton, Ohio, April 1990.

[9]Personal communication with G. Peterson, April 1990.

[10]NAS/NRC, p. 1.

[11]Lubin, p. 11.

production applications of primary structures. The airframe industry became quite adept at producing large, laminated, fiberglass structures (such as radomes). However, as far as production aircraft were concerned, these were secondary structures that did not carry large loads, were not particularly stiffness critical, and thus were not subject to the close analytical, manufacturing, and testing scrutiny that accompanies primary structures. In fact, the Air Force spent ten to fifteen years trying to improve the stiffness of fiberglass but this was curtailed as boron and other materials emerged. In the end, the fiberglass experience was probably a necessary, but not sufficient, condition to achieving advanced material capabilities.

Research In Applications of Advanced Composites

Once the advanced composite materials had been developed to the point where usable quantities were available to the industry, research into structural applications began.[12] Perhaps the most important role the Air Force has played in the development of composites technology has been as "seed money" supplier and technology advocate to an industry that had little nonmetallic, advanced-materials capabilities. From the mid-1960s to the present, the Air Force technology organizations encouraged the development of advanced design and manufacturing capabilities through R&D funding and Independent Research and Development (IR&D) arrangements.

Funding of design and demonstration efforts served a number of interrelated purposes:

- To begin to build an advanced, nonmetallic materials capability where almost none had existed before;
- To motivate the airframe industry to recapitalize and invest in composites technology;
- To counter the airframe industry's natural instinct to use the cheapest, least-risk material to meet the requirements.

The first bullet serves as a reminder that up until the mid-1960s, the experience of the airframe industry was in metallic load-bearing structures. Plastics and fiberglass-reinforced composites had been used for twenty years but only in secondary structures. An important component in building an advanced composites capability was the generation of a technical database that was available to the industry at large.

[12]About 1965.

The second bullet reflected a longer term goal; to induce the industry to invest in a new technology that was, in many fundamental ways, counter to the established metallic ways of doing business. Only through repeated demonstrations of the utility (and viability, through service experience) of advanced composites in aircraft structures was this likely to come about.

The third bullet acknowledges an economic reality of the marketplace. The airframe industry would tend to shy away from a new technology that, through lack of familiarity and related infrastructure, might lead to cost and schedule problems for production programs. However, industry was receptive to performing contract R&D on advanced materials; it just was not very anxious to risk it on production programs. Gradually, as Air Force commitment to the technology was maintained and as flight experience revealed that the new kinds of problems associated with composites could be solved, the airframe industry began (around 1975) to invest more heavily in advanced materials capabilities.[13]

The Advanced Development Program (ADP)

As soon as the advanced materials were available (1965), the Air Force initiated the Advanced Development Program (ADP) within the Materials Laboratory. The perception of the necessity for a development program of this type grew out of the Project FORECAST work. The main goals (admittedly interrelated) of the ADP program seem to have been:

- To design, manufacture, and test advanced composite airframe structures;
- To foster long-term, advanced materials capabilities within the airframe industry to be used for production of future aircraft;
- To initiate the technical databases that would be required for widespread acceptance of these materials.

Initially, the projects funded through ADP concentrated mainly on materials substitution (composites for metals) in existing flight structures. Metal components were evaluated with respect to their potential to be replaced by an equivalent composite design. Factors such as part contour, part loading (primary or secondary), part size, and service temperature were considered in the selection process. For some research, development, test, and evaluation (RDT&E) and production programs, the feasibility of replacing the metallic design with the composite design was assessed.

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[13]Personal communications with S. Dastin (Grumman Aerospace, New York, August 1990) and R. Rapson (Air Force Materials Laboratory, Wright-Patterson AFB, Ohio, August 1990) support this assertion.

The materials were so new that the Materials Laboratory often donated the boron (and later, graphite) filaments to industry for particular programs. For example, in 1967 Grumman was contracted to design and fabricate an FB-111 wing box extension out of boron/epoxy; the Materials Laboratory supplied 120 pounds of boron filaments.[14]

During the first year of ADP, applications to helicopter rotor blades and reentry vehicles were funded. Other demonstration efforts between 1965 and 1970 involved structures on the F-4, F-100, C-5 aircraft, as well as missile and engine components. The first advanced composite demonstration item to emerge from the ADP program was the F-111 horizontal stabilizer (1967) by General Dynamics. On most items, weight savings of 10 to 30 percent were generally achieved with respect to the original metal designs.

Perhaps the most significant limitation of the ADP program was the very limited number of assemblies that were built. These were not production programs, and quantities were therefore small. While critical design, manufacturing, and test experience was gained by the industry, this experience was limited. Also, it seems likely that the small quantities of composite structures that were being requested would not have increased industry's motivation to develop, for example, automated fabrication for composites. Extended flight experience and the chance to apply these materials to production programs were necessary to convince the industry that these materials were indeed viable structural materials and to begin to invest in this relatively expensive structural technology.

A measure of the early success of the ADP program is illustrated by the increase of the total number of advanced composite structures in military service during the 1970s. By the end of 1970, there were very few boron/epoxy components in service; by 1975, there were about 400 to 500 composite structures (both boron and graphite). And approximately 3000 were estimated to be in service by 1980.

Finally, it should be noted that not all early development activities for composites were funded through R&D. Many projects were contractor-initiated IR&D, which involved production money. Companies such as General Dynamics (GD),[15] Vought Aeronautics,[16] and

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[14]Air Force Materials Laboratory, Advanced Composites Division, *Advanced Composites Status Review,* hosted by Grumman Aerospace Corporation on April 8–9, 1970, Bethpage, New York, DTIC Report No. AD-B958 770, U.S. Government Printing Office, 1987, p. 1.

[15]For example, GD performed research on a metal-matrix (boron/aluminum) design for an access panel on the F-106; see *Advanced Composites Status Review,* 1970, p. 173.

[16]For example, Vought developed composite structures for the A7-D (wing tip, fuselage panel, speed brake); see *Advanced Composites Status Review,* 1970, p. 79.

Douglas[17] received some degree of reimbursement for their composites-related IR&D activities of the late 1960s.

Early Production Applications of Advanced Composites

While the Air Force pushed hard on the R&D of composites technology, the initial applications for new aircraft were more difficult to come by. Reasonable success with the ADP projects led to the first design of an advanced composite part for a new production aircraft (not simply a substitute for an existing metallic component). This was a boron/epoxy skin section (primary structure) on the Navy's F-14 vertical stabilizer by Grumman.[18] Expressed as a percentage of the total structural weight of the F-14, this application of boron/epoxy amounted to less than 1 percent of the aircraft. Composites were then incorporated into the Air Force's F-15[19] and F-16,[20] although still in limited amounts (less than 3 percent).[21] Aircraft of the late 1970s and early 1980s began to use more composites (10 to 25 percent). Applications included wing skins on the Navy's F-18 and both skin and substructural components on the AV-8B. However, it has taken until the late 1980s and early 1990s to start development and production of aircraft designs with levels of composites approaching 50 percent.

Although the Air Force had funded the majority of advanced composites R&D, it was the Navy's critical need for weight reduction (to meet aircraft carrier operations requirements) that provided the first opportunity for incorporation of composites into a new design. During the 1970s and early 1980s, the Navy consistently fielded aircraft with higher levels of composites than did the Air Force.

Around 1975, the airframe industry seemed to develop much more interest in increasing their composites capabilities. Although the reasons are not entirely clear, it is possible that this interest was a reaction to two general factors:

- A few years of relatively positive flight experience;
- The perception, by industry, that the military was committing to this technology for use in future weapon systems.

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[17]For example, Douglas developed a graphite wing landing flap for the A-4; see *Advanced Composites Status Review*, 1970, p. 122.

[18]Partial funding for the design and fabrication of this component came from the ADP.

[19]Speed brakes.

[20]Vertical and horizontal stabilizer skins.

[21]Note that the first production application (although not for a new aircraft) of a graphite/epoxy structure was an underwing fairing of the F-111 (late 1971).

The first bullet suggests that the industry may have relaxed somewhat as preliminary flight experience indicated that composites were legitimate structural materials that could perform their function over time and under actual service conditions. This is not to say that technical problems did not crop up. For example, concerns arose about weight gain and possible strength reduction through the mechanism of moisture absorption by the epoxy. The significance of internal delaminations[22] to part stiffness and strength was also debated. There were also concerns about the large variability of advanced composite material properties and about the amount of laminate testing that was necessary to adequately characterize all of the different laminated configurations (number of plies, fiber angles, ply thicknesses, etc.) that would be used in an aircraft design. Testing was particularly important given the large variability in properties and the lack of adequate analytical capabilities. Still, there was a growing attitude that these technical problems could be resolved with more R&D and production experience.

The second bullet follows in part from the first. The industry may have believed that composites held out the potential for performance gains that the military would find increasingly difficult to ignore despite the high cost of doing business with these materials. This perception, if true, may have been very important since the airframe industry is likely to be highly motivated to pursue those technologies that appear desirable to the services because they often lead to lucrative production contracts.

Summary

The Air Force has always been the single most important funding source for the development of advanced composites. This was particularly true from the early days of fundamental research (ca. 1960) to what might be called the "initial maturity" of application of composites technology (ca. 1975). In addition to providing funds for research, the Air Force also supplied technical management and a long-term commitment to the development of the technology, factors that many sources believe were critical to success.

While the Air Force demonstrated the feasibility of the technology, some believe that the supporting technologies (e.g., manufacturing techniques) may not have been given adequate attention; a problem that is still being addressed today but through a wider range of participants. However, given the complexity of the technology and the fact that it continues to grow and evolve, it is doubtful that any one agency would have the resources to single-handedly resolve all of the technical and cost issues.

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[22] A debonded area between adjacent plies within the laminate; delaminations can occur during manufacturing or in service.

The era of "high-content" composite aircraft design has really just begun in the last five to eight years. The new aircraft that are beginning to emerge contain an order of magnitude more composites than their predecessors of the 1970s. New designs contain composite structures that are much more complex in terms of load-bearing requirements, size, contour, weight, etc. The Air Force has continued to sponsor R&D in composites technology, and it is doubtful, given the level of commitment to composites that the Air Force is making in terms of production aircraft, that it will ever be able to walk away from its R&D function and feel that the job is done. The emphasis may change,[23] but the complexity of the technology will likely demand an ongoing commitment from the Air Force.

OTHER AIR FORCE FUNCTIONS

Supporting Technical Work in Academic Institutions

The Air Force supported basic technical work in academic institutions. There were at least two benefits to this kind of support. The first was that the number of technical personnel trained in the fundamentals of composites grew, thus supplying the work force that would be needed on an increasing number of programs utilizing composites. The second benefit was that academic institutions, while not particularly suited to working on the technical issues associated with specific weapon systems, are well qualified to perform more basic research that systems-oriented, advanced development work must draw upon.

According to one source,[24] the Air Force actively sought to engage key academic researchers in the issues of composites early in the development process. The hope was that once key academicians were involved with and interested in the issues associated with composites, they would be motivated to teach it to their students.

Academic institutions began to be more heavily involved in researching and teaching advanced composites during the early to middle 1970s. There is evidence to suggest that the technology has become permanently enmeshed in the academic environment:

- The large number of universities that now have composites research programs;
- The large number of technical associations and seminars (often targeted towards practicing designers and engineers) that are devoted to composites.

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[23]Possibilities include: low-cost manufacturing techniques with thermoplastic materials; supportability and repairability of composite structures; low-observability; metal and ceramic-matrix composites.

[24]Personal communication with Dr. Alan Lovelace, November 1990.

Thus, members of the first generation of engineers with significant academic exposure to composites are still fairly young (early to late thirties) and are not likely to have had design/production experience with more than two major aircraft systems containing extensive amounts of composites. If the relative age of a technology can in some sense be compared to the age of its oldest indoctrinated practitioners, then advanced composites are approaching early adult maturity.

Publication and Dissemination of Technical Results

Another important technology-development activity that the Air Force has engaged in is the publication and dissemination of research results. In the area of composites, sources have claimed that AFML technical reports were an important means of disseminating technical information around the industry. The Air Force also funded the development and distribution of several editions of design (starting in the late 1960s) and fabrication guides for the benefit of the industry. These design and fabrication guides now serve as interesting references, but they contribute little to design activities. In part, this is due to the changing nature of the materials themselves and also to the fact that each company tends to follow its own methodology for the design and manufacturing of composite structures. The very nature of composites has made it much more difficult to find (and agree to) standard design and manufacturing procedures.

There are limits to the benefits of these publications with respect to maintaining design capabilities. For example, one view that has often been expressed is that research of a more basic and broad based nature can be disseminated more effectively than work that is oriented towards specific weapon systems. Dissemination of results is also becoming increasingly hampered by "black" programs, which can put limitations on publication.

4. OTHER AGENCIES SPONSORING COMPOSITES RESEARCH

There are several government agencies outside of the DoD that sponsor research in advanced composites. Although the goals of such research programs do not specifically address the needs of military airframes, the degree of their success (or failure) to impact other markets can have a substantial effect on future Air Force weapon systems. Most current research outside of the DoD is geared towards commercial markets and is motivated by such factors as: reduced cost, innovative manufacturing methods, life prediction, quality assurance, and damage tolerance/inspection. Substantial volume usage of advanced composites by commercial industries is a key to the cost reduction of composites technology.

A recent report by the Department of Energy[1] identified nearly 800 projects (active or recently completed since 1985) sponsored by the Federal government in the area of advanced polymer-matrix-composites research. According to the report, more than half are oriented towards developing improved materials; about one-third are concerned with structures technology; and about one-sixth are related to manufacturing technology "despite the need for efficient, economical methods of manufacturing products constructed of polymer-matrix-composite (PMC) techniques required for PMCs to gain widespread acceptance."

NASA

NASA has been sponsoring research in advanced composite aircraft structures since the 1970s. NASA's efforts[2] in this area have been principally oriented towards commercial transports and have concentrated on generating the technical data necessary to obtain Federal Aviation Administration (FAA) certification of selected parts. For example, NASA sponsored a service evaluation of Boeing 737 spoilers (made out of graphite/epoxy) and accumulated more than 400,000 hours of flight experience from 1973 to 1978. NASA also sponsored the design and fabrication of elevators and horizontal stabilizers for Boeing 727 and 737 aircraft; a number of these structures have been in commercial use since 1980. The goal of such programs is to convince aircraft manufacturers that composites are reliable, that they provide benefits over metallic structures, and that, with further research, they can be cost competitive. To date, the rate of incorporation of composites into large commercial aircraft has been relatively slow (although a few exotic, but small, general aviation aircraft have been developed with high percentages of graphite/epoxy).

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[1]Walcoff & Associates, Inc., p. ES-3.

[2]NASA has also sponsored considerable composites research relating to space activities.

A reduction in NASA's budget curtailed their activities in aircraft-related composites during the early 1980s. Very recently, however, NASA's budget has been increased and they are funding a high-dollar research program called the Advanced Composites Technology (ACT) program. ACT evolved as the result of an assessment of national capabilities with respect to the production of composite aircraft. This assessment was performed by the National Research Council during the mid-1980s. NRC concluded that a more rapid insertion of technology could be achieved by a program that coordinates the efforts of NASA, DoD, academia, and industry.

The primary goal of ACT is to increase the performance of composite structures while decreasing the costs of fabrication so that these technologies will be more rapidly incorporated into new aircraft. The program emphasizes research on structural design concepts and cost-effective fabrication techniques using advanced organic matrix materials (i.e., no metal or ceramic matrix materials). NASA and the DoD are expected to conduct annual reviews on composites research and to integrate their technical accomplishments. NASA funding of the program is significant; between $20 and $30 million a year between 1990 and 1994. Funding beyond that timeframe has yet to be established. Most projects received more than $1 million, but three projects (run by McDonnell Douglas, Boeing, and Lockheed) received in the range of $22 to $24 million apiece.

NATIONAL SCIENCE FOUNDATION

The dollar amount of research in advanced composites that is funded by the National Science Foundation (NSF) is small; on the order of $1 to $2 million a year. However, NSF sponsors programs that could impact military airframe structures. For example, under NSF funding, Stanford University was funded to develop a small machine that will form large, complex, composite shapes from flat, thermoplastic-matrix laminates.

NSF also sponsors the creation of university-based research centers in specific technical areas. For example, in the area of advanced composites, there is the Center for High-Performance Polymeric Adhesives and Composites at Virginia Polytechnic Institute.

5. FUNDING DATA FOR ADVANCED COMPOSITES DEVELOPMENT

BACKGROUND

The total value of DoD weapon systems employing advanced composites is estimated to have been about $80 billion in 1990.[1] Funding data, particularly with respect to the early years of advanced composite development, are scarce. While some gross estimates of the levels of government R&D funding in this area are made, it was not possible to systematically estimate the dollar contributions of private industry nor the effects of IR&D arrangements that may use money allocated for production programs to perform specific research.

There are several government agencies that currently support research in the area of advanced composites. These include: the Department of Defense (DoD), the National Science Foundation (NSF), the Department of Transportation (DOT), the Department of Energy (DOE), as well as the Strategic Defense Initiative (SDI), NASA, and Defense Advanced Research Projects Agency (DARPA) programs. Of these sources of funding, the largest by far are DoD's and NASA's. The DoD contribution to this technology area is unique since it is the oldest, largest (in terms of dollars), and continuous source of support for the development of advanced composites in military aircraft. The other agencies are engaged in composites research that may be of indirect value to military aircraft, but they are generally much smaller efforts with very different research objectives. Outside of DoD, NASA has the most significant research program in composites and coordinates the most with DoD.

Within the DoD, the Air Force has been and continues to be the most significant source of research funding in advanced composites. One source[2] estimates that the sum of government 6.1 to 6.3a funding in the area of advanced composites since the early 1960s is about $1 billion. This figure does not include manufacturing nor structural and flight testing. If these are included, the estimates of the total increases to "several" billion. Another source[3] estimated that about $3 billion were spent in this country to produce advanced composite primary structures.

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[1]Walcoff & Associates, Inc., p. 4.

[2]Personal communication with J. Persh, Staff Specialist for Materials and Structures, Office of the Deputy Director of Defense, Washington, D.C., August 1990.

[3]Personal communication with S. Dastin, August 1990.

Currently, the DoD accounts for about two-thirds of all federal R&D dollars (about $100 million in FY 1987) spent on all types of advanced composites.[4] Total DoD funding for research into polymer-matrix composites (e.g., thermosetting epoxies traditionally used in military aircraft) has ranged from about $30 to $70 million per year since the late 1980s. These figures do not include engineering development, operational systems, or classified programs.[5] Since the late 1970s, government-sponsored research into new types of advanced composites has, in a dollar sense, become nearly as important as research in polymer-matrix composites.[6] These newer forms of advanced composites such as metal-matrix, ceramic-matrix, and carbon-carbon, have yet to be applied in a production aircraft, but this should begin to occur within the next five to ten years, perhaps with the Air Force's Advanced Tactical Fighter (ATF).

ESTIMATED FUNDING LEVELS: 1958–1990

Figure 6 shows a very rough estimate of the levels of Air Force R&D funding over time with respect to the development of advanced, polymer-matrix composites for aircraft use.[7] Note that the funding levels are expressed in millions of 1991 dollars. Also note that this curve does not reflect production programs, IR&D arrangements, the effects of classified programs, nor the contributions from the other military services.[8]

The dashed line connecting the funding levels of the late 1950s to the early 1960s reflects a gap in the sources of data that were used. The abrupt rise beginning in the middle 1960s reflects the level of effort that was being expended during the first years of the composites Advanced Development Program (ADP). At this time, the technical goal was to qualify boron/epoxy material systems for use in primary aircraft structures. From 1970 to 1985, the level of Air Force funding seems to have been fairly constant (around $30 million per year). From 1986 to the present, Air Force funding has experienced significant increases (peaking around $50 million). The total area under the curve represents about $1 billion worth of AF R&D effort over a span of almost thirty-five years.

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[4]U.S. Congress, Office of Technology Assessment, *Advanced Materials by Design,* OTA-E-351, U.S. Government Printing Office, Washington, D.C., June 1988, p. 271.

[5]Walcoff & Associates, Inc., p. 4.

[6]U.S. Congress, Office of Technology Assessment, June 1988, p. 271.

[7]This curve results from a subjective piecing together of data from a number of sources, including: funding data from L. Kelley, of the Advanced Development Program in the Air Force Flight Dynamics Laboratory, May 1990; funding data from the Air Force, Force and Financial Planning (F&FP) database (1990); and several older National Academy of Sciences/National Research Council reports.

[8]Particularly during the early years, contributions from the other services were small with respect to Air Force funding of aircraft-related, advanced composites technology.

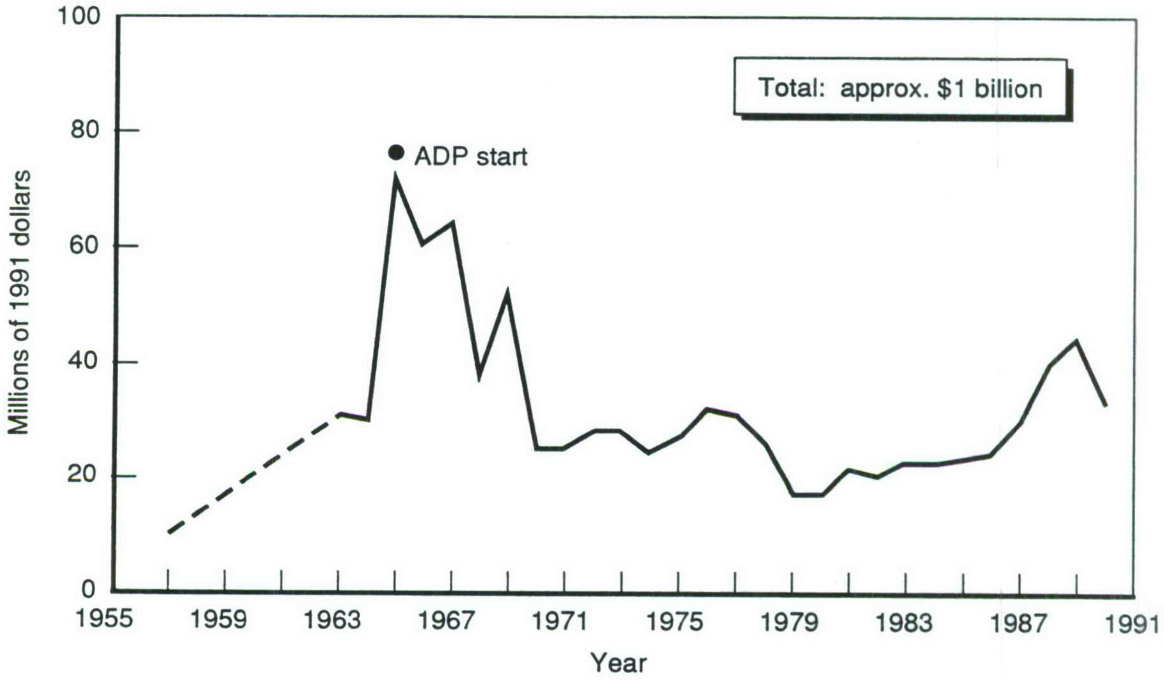

Figure 6—Air Force R&D Funding Estimates for Advanced Composites Technology

AN ALTERNATIVE FUNDING ESTIMATE FOR 1966

The early development of advanced composites was in full swing during 1966. According to Fig. 6, total Air Force funding was about $58 million. As a check on this number, an alternative estimate was made in the following manner.

In the mid-1960s, the majority of R&D funding was sponsored by the Air Force through the Materials Laboratory. Although the Materials Laboratory publishes an annual report on the status of all of their active contracts, these reports do not generally contain contract values. An exception to this rule occurs in the annual report covering 1966.[9] In this document, the following information is supplied about each contract (both in-house and contractor-supplied research):

- Project title and brief description
- Contractor
- Contract number

[9] Air Force Materials Laboratory, *Abstracts of Active Contracts*, Report AFML-TR-66–377, December 1966.

- Contract duration
- Total contract value

For the purposes of this funding estimate, each contract description was examined and a subjective determination was made as to whether the project was relevant to the development of advanced composites. "Relevancy" was defined to include any work on the following subjects (called "technical thrusts" in Figs. 7 and 8):

- Materials development (fiber, matrix), processing, and pilot production
- Design/development of aircraft structures
- Design/development of engine components
- Manufacturing and inspection techniques

Each contractor was categorized as one of the following:

- Major airframer
- Subtier company
- University

These data were assembled on a spreadsheet and funding levels were converted to 1991 dollars.[10]

In Fig. 7, the two largest contracts in each of the subjective "technical thrust" areas are described in terms of: project title, contractor, total contract value (over the entire life of the contract, not just for 1966), contract number, and duration. The range of total contract values for the remaining contracts in each area are also given.

Clearly, the largest composites-related contracts were in the area of aircraft design, with total contract values of $12.7 million (Boeing) and $11.5 million (General Dynamics), and with contract durations of two to three years. All other contracts in the aircraft design area were much smaller, with total contract values between $300 and $800 thousand. The next largest contracts were in the area of materials research/production, the largest of these with total contract values of $3.7 million (Union Carbide) and $3.4 million (General Electric).

[10]For those contracts (less than 20 percent) where the contract duration was not specified, 24 months was assumed. An assumption of this type was necessary in order to estimate the total value of composites-related R&D contracts for the year 1966. Using the simplest possible approach, total contract values were divided by contract duration, annualized, and then converted to 1991 dollars (assuming original contract values in 1966 dollars).

Technical thrust	Contractor ( ) contract number		Two largest contracts: Total contract value[a]	Two largest contracts: Duration (months)	Total value ranges for other contracts[a]
Aircraft design	Boeing	(A)	12.7	30	0.3–0.8
	General Dynamics	(B)	11.5	32	
Engines	General Electric	(C)	1.4	--	0.1–1.3
	General Electric	(D)	1.3	20	
Materials research and pilot production	Union Carbide	(E)	3.7	--	0.1–2.3
	General Electric	(F)	3.4	--	
Manufacturing and inspection	Aerojet	(G)	1.6	22	0.1–0.7
	Monsanto	(H)	0.9	21	

[a]Millions of 1991 dollars

(A) AF33(615)-5275 (B) AF33(615)-5257 (C) AF33(615)-3362 (D) AF33(615)-5319
(E) AF33(615)-2760 (F) AF33(615)-2126 (G) AF33(615)-3313 (H) AF33(615)-3310

Figure 7—A Look at the Largest AFML-Funded Contracts Active in 1966

Engine research and manufacturing/inspection techniques received substantially lesser amounts.

In Fig. 8, an approximate "snapshot" of AFML-sponsored composites research for the year 1966 is given both in terms of "technical thrust" and "contractor type." In all, a total of seventy active contracts were identified; with a total contract value of about $75 million (1991). Almost fifty of these contracts were related to materials research and pilot production; only seven were clearly identified with design of aircraft structures. Research funding just for the year 1966 is estimated to have been about $37 million: nearly $20 million in materials research/pilot production, and about $11 million in the design and development of aircraft structures.

The 1966 total of $37 million can be compared to the curve in Fig. 6, which indicates a funding level of $58 million. The sources of discrepancy between these two results may be difficult to determine. Figure 6 does reflect significant amounts of early manufacturing-technology funding (Air Force Program Element 7.8) for composites that may not be reflected in the AFML report. It is also possible that some projects that were judged not to be

	Number of contracts	Approximate value of all 1966 contracts[a]
Technical thrust		
Aircraft design	7	11.1
Engines	5	2.9
Materials research and pilot production	47	19.9
Manufacturing and inspection	11	3.3
Totals by technical thrust	70	37.2
Contractor type		
Aircraft design	8	10.9
Subtier company	55	24.9
University	7	1.4
Totals by contractor type	70	37.2

[a]Approximate aggregate value of contracts for 1966 expressed in millions of 1991 dollars

Figure 8—Distribution of AFML Contracts for 1986

composites-related in the AFML report, in fact, really were related. If funding for manufacturing technology of composites for 1966 is eliminated from the curve in Fig. 6, the total of $58 million is then reduced to about $48 million.

6. CONCLUSIONS

THE ROLES OF THE AIR FORCE IN THE DEVELOPMENT OF ADVANCED COMPOSITES

The development of advanced composites must be viewed within the context of the rapidly expanding mission requirements that began to fall within the purview of the Air Force during the late 1950s. At that time, the potential utilities of new systems (e.g., ballistic missiles, supersonic aircraft, reentry vehicles) were thought to be constrained by materials technology. There was a growing realization in the defense communities that advanced materials of all types (e.g., refractory metals, composite materials, ceramics, plastics) had to be developed if these new systems were to perform adequately in these new flight environments.

A consensus arose within the DoD and important advisory groups that the Air Force would find it progressively more difficult to solve its emerging materials problems within the constraints of existing conventional materials. Therefore, the Air Force was strongly encouraged to take a leading role in the development and application of new materials since it had the strongest need. Within this context, the Air Force aggressively pursued the development of advanced composites. The important actions of the Air Force with respect to the development of advanced composites technology might be summarized as follows:

- Identification of a promising air-vehicle technology;
- Major source of R&D funds for technology development prior to (and long after) initial flight applications;
- Technology advocate;
- Establishment of technical feasibility through flight-demonstration articles;
- Generation of early, nonproprietary, technical databases for the industry to draw upon.

These actions led to the development of sources for advanced composite materials and to the motivation of the airframe industry to develop advanced composite design and manufacturing capabilities. This change in the industry was likely the consequence of the Air Force employing R&D "seed" money to quickly establish technical feasibility. Perhaps as important as technical feasibility was the industry's belief that this was a technology that the Air Force was committed to utilizing in production systems of the future.

TIMES REQUIRED FOR TECHNOLOGY DEVELOPMENT

Another important context to keep in mind is that the modern era of advanced composites technology was preceded by about twenty years of R&D and flight experience with the original modern composite material system (fiberglass-reinforced plastics). The design and testing experience of the 1940s and 1950s verified the need for advanced materials with greater stiffness. During this time, the general concept of fiber-reinforced plastics (with all of its implications for design, manufacturing, inspection, etc.) became more familiar to DoD and industry, and thus, this experience formed some of the conceptual framework over which advanced composites technology would be developed in the 1960s and beyond.

With respect to the first truly advanced composite material system (boron/epoxy), the transition of this material from experimental material to validated engineering material appropriate for use in primary aircraft structures took the Air Force about fourteen years (1958–1971). Once reasonable quantities of the material could be produced (by 1965), the Advanced Development Program within the Materials Laboratory funded the development of design and manufacturing capabilities within the airframe industry through a series of flight-demonstration articles. By 1970, boron/epoxy had a structural role in a new production aircraft (F-14). By the mid-1970s, graphite/epoxy had quickly surpassed boron as the advanced fiber of choice.

It took about five to seven years of flight experience with demonstration articles and initial production hardware before the airframe industry began to commit their own resources to these materials. Firms preferred to be funded to advance technology through direct contract R&D and were reluctant to risk weapon system proposals on new and unfamiliar technology.

Subtier companies[1] played a key role in the technology development process. Two-thirds of the R&D money (associated with composites research) in the AFML report on active contracts in 1966 went to subtier companies; only about 30 percent went to the large airframe manufacturers. Much of the research at the subtier level was aimed at further development of the composite materials themselves. It was also noted that primes do not want to get into the materials business because of the large amounts of investment (and materials expertise) that are required.

[1]Those companies who support the major airframers.

THE RELEVANCE OF THE COMPOSITES EXPERIENCE TO OTHER TECHNOLOGY DEVELOPMENT

Making inferences about the general subject of technology development based on the Air Force's experience with advanced composites is not a simple matter. However, the following points suggest themselves:

- The Air Force can play a critical role in the identification and development of new air-vehicle technologies.
- The technology-development process evolves over a period of many years and requires budgetary commitments that may extend far beyond the point of initial applications. In the case of advanced composites, this commitment has lasted for about thirty years and will continue into the future.
- Long-term growth of critical technologies is in part dependent upon the degree to which the technologies become active research interests of the academic communities.

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